



RESEARCH DEPARTMENT

TESTS OF THREE SYSTEMS OF BANDWIDTH COMPRESSION OF TELEVISION SIGNALS

Report No. T-080

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THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION



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SUMMARY

This report describes an investigation into three similar methods of reducing the bandwidth required for the transmission of television pictures. The three methods all involve the isolation of the essential brightness changes in the picture; these are redistributed to occur at a uniform rate for transmission. A second signal must be transmitted in order to allow correct repositioning of the brightness changes in the final picture. Partial instrumentation has been carried out and the methods assessed as regards their bandwidth requirements and resultant picture quality.

1. INTRODUCTION

A considerable amount of effort, both theoretical and practical, has been devoted to the problem of reducing the channel capacity required for the transmission of television signals. The channel capacity can be expressed in terms of the product of the signal-to-noise ratio in decibels and the bandwidth necessary. Whether the reduction is utilized by reducing the bandwidth or the required signal-to-noise ratio depends on the medium through which the signal is to be transmitted. For long-distance cable transmission the bandwidth might be the major consideration, but for some forms of radio link the signal might be arranged to require a very low signal-to-noise ratio at the expense of bandwidth. This latter case applies to pulse-code modulation or frequency modulation.

One obvious reason for the desire to reduce the channel capacity has been the need to increase the distance over which television signals can be transmitted on a point-to-point basis, without undue loss of picture quality. So far no completely satisfactory system of channel reduction has been evolved. Indeed, parallel effort aimed at improving the performance of long-distance television links has been so successful that, as regards the continent of Europe, the need for channel reduction no longer exists. The problems involved, however, in the transmission of television over long sea paths could still be considerably alleviated by an efficient and practical system of channel-capacity reduction.

All the methods so far proposed are of such a complexity as to rule out any immediate prospect of their application to television broadcasting. The receivers would be too expensive for the domestic market. In this report we consider the system as if for a link in a broadcasting network, so that cost or complexity of the receiver has not been taken seriously into account. The channel capacity required by

each of the systems considered is far too great for any long-distance cable which is likely to be entirely at the disposal of a broadcasting authority in the near future. The requirements of each system will be expressed in terms of bandwidth and receiver signal-to-noise ratio for direct comparison with the conventional system of television broadcasting and radio links.

It is of interest to consider the channel capacity available for the transmission of conventional television signals using the 405-line British standard. Shannon¹ has derived a formula for the upper bound to the capacity of a channel using a transmitter limited by its peak power.

$$C \leq W \log_2 \frac{\left(\frac{2}{\pi \epsilon}\right) S + N}{N} (1 + \delta) \quad (1)$$

where C = the channel capacity in bits/second
 S = the peak signal power
 N = the noise power (assumed "white" noise)
 W = the bandwidth of the channel in cycles/second
 δ = arbitrarily small
 $\epsilon = 2.718$

From experience we can say that a bandwidth of 3 Mc/s and a peak-signal to r.m.s.-noise ratio of 30 dB permit the transmission of acceptable television pictures. Because $S \gg N$, and ignoring δ , the maximum capacity of such a channel is given by

$$C \leq 3 \cdot 10^6 \log_2 \frac{2000}{\pi \epsilon} \quad (2)$$

that is,

$$C \leq 24 \cdot 10^6 \text{ bits/second}$$

Any satisfactory system of channel-capacity reduction should result in pictures at least as acceptable, subjectively, as the conventional picture with a 30 dB signal-to-noise ratio, and require a capacity appreciably less than $24 \cdot 10^6$ bits/second.

In published papers on channel-capacity reduction the channel capacity associated with conventional television transmission is often taken to be appreciably higher than that derived above, even when allowance is made for differing standards; this obviously leads to a comparison more favourable to the alternative system under discussion.

In this report it is intended to describe investigations carried out in order to assess the merits of three proposed systems of reducing the bandwidth required for the transmission of television signals. The three systems all depend on the assumption that the number of significant changes of amplitude, in television waveforms, is considerably less than the number of possible changes, and that the information about these changes, if suitably coded, can be transmitted in a bandwidth narrower than that required for the original waveform.

The investigation did not extend to the complete instrumentation of any of the systems and in none of them was the waveform actually reduced in bandwidth by coding. The purpose was to observe the picture quality obtainable when the number of brightness changes was restricted, and to count the number of brightness changes per line and per picture. Some of the problems involved in the engineering of a practical system are discussed.

2. DESCRIPTION OF THE SYSTEMS

The first system investigated was that due to Gouriet² who suggested that, by quantizing the picture waveform into relatively few discrete amplitude levels, an acceptable picture could be obtained with relatively few changes of amplitude for each picture. An example given was that if the waveform were quantized into six levels, the average number of amplitude changes per line would not exceed fifty for most pictures. This would require an average of 100 symbols per line because the position of each change, as well as the associated amplitude, must be transmitted. The conventional system (for the 405-line standard) is capable of nearly 600 changes per line, including the time normally occupied by the synchronizing signals. Thus a reduction of 6:1 should be possible in the number of signals needed to be transmitted. Gouriet points out that this does not necessarily mean a 6:1 reduction of the required channel capacity because the position information would require a much better signal-to-noise ratio than the 30 dB necessary for conventional television. This point will be dealt with more fully in the section dealing with the investigation into this system, which we shall refer to as the "quantized-video" system.

The second system is a modification of the first, to take advantage of ideas contained in an earlier system described by Kretzmer³ and a later system described by Schreiber and Knapp.⁴ One major disadvantage of quantizing the video waveform into a few levels is the inability to reproduce the gradual changes of brightness essential for the realistic portrayal of many three-dimensional objects. In this second system the video waveform is divided into two waveforms, one containing only the low-frequency components below, say, 100 kc/s or even 300 kc/s, and a second waveform consisting of the difference between the original waveform and the low-frequency component waveform. This difference waveform comprises the sum of those components having frequencies above the chosen frequency of division, and can be quantized in amplitude and coded into a reduced bandwidth as in the case of the "quantized-video" system. The low-frequency waveform can be transmitted without quantization and added to the reconstructed, quantized, high-frequency component at the receiver. This system permits the reproduction of gradual changes of brightness by means of the low-frequency waveform, edges and small details being approximately reproduced by the quantized high-frequency waveform. The quality of the reconstructed picture is, of course, very dependent on the bandwidth allocated to the low-frequency components and the system has been investigated with two bandwidths for this purpose, 100 kc/s and 300 kc/s. The system will be referred to as the "quantized-highs" system.

The third system is based on the methods described by Schreiber, Knapp and Kay.⁵ The low-frequency components are transmitted without alteration and, at the receiver, added to a waveform representative of the high-frequency components of the original waveform. This method differs from the "quantized-highs" system in the derivation of the high-frequency component waveform. In this third method, which we

will call the "synthetic-highs" system, the video waveform is differentiated with respect to time and then quantized into a few discrete levels. This results in a waveform consisting of pulses occurring at the points of maximum change of amplitude of the original waveform. The amplitude of each pulse approximately represents the rate of change of amplitude at the particular point on the video waveform. These pulses can be coded for bandwidth reduction and, after decoding at the receiver, passed through a special shaping network before being added to the low-frequency waveform which has been separately transmitted.

3. THE "QUANTIZED-VIDEO" SYSTEM

For the investigation into this system an electronic waveform quantizer was constructed. The number of levels into which the waveform was quantized was controlled by means of a single control knob. The device consisted basically of twelve bi-stable circuits each set to change its state at a different trigger voltage level. The quantization was achieved by arranging that, as the input video waveform increased through each one of twelve predetermined voltage levels, one of the twelve bi-stable circuits changed state and produced a sudden change of output voltage. The rate of increase of the output voltage was largely independent of the rate of change of the input voltage. Similarly, as the video waveform voltage decreased through each one of twelve particular voltage levels one of the twelve "bi-stables" changed its state and produced a sudden reduction of the output voltage. The voltage level at which each bi-stable operated when the input voltage was increasing was higher than that when the input voltage was decreasing. This "backlash" effect was adjustable but could not be made to disappear completely.

Fig. 1 shows the manner in which a waveform was quantized and how the backlash was capable of causing a reduction in the number of transitions from one

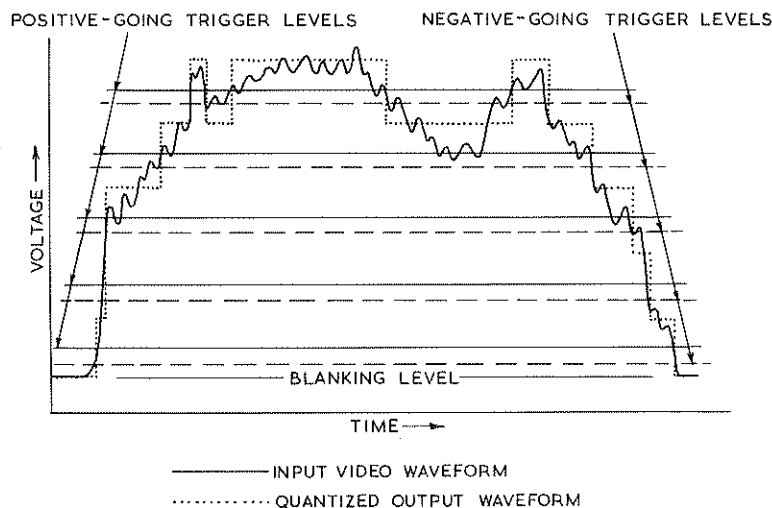


Fig. 1 - The quantization of a continuous waveform, showing the effect of "backlash" in reducing the number of transitions due to noise or fine detail. There are thirteen transitions, although the continuous waveform crosses positive-going trigger levels thirty times

level to another because of noise or fine detail. If the output voltage changed level each time a trigger-voltage level was passed in either direction, the number of transitions in Fig. 1 would be thirty instead of thirteen. Unfortunately, this reduction is not achieved without cost. The presence of a noise "spike" can cause a slowly changing voltage to trigger a bi-stable circuit earlier than would have been the case had no noise been present. If the peak-to-peak noise voltage is insufficient to overcome the backlash, the bi-stable circuit will not return to its previous state at the end of the noise spike. As a result, contours associated with relatively slowly changing parts of the waveform become somewhat ragged in outline and continually change their outline because of the random character of the noise.

The quantized waveform, besides being displayed on a picture monitor for subjective assessments, was differentiated with respect to time, and the resulting pulses were limited in amplitude and then shaped. These relatively uniform pulses were then fed to counters.

In order to explain the purpose of these counters it is appropriate to describe the basic principles of the method of bandwidth reduction suggested by Gouriet. This is best explained by reference to Fig. 2. The quantized video waveform is shown at (a). This waveform is differentiated with respect to time (waveform (b)) and then full-wave rectified and limited in order to produce the uniform-amplitude pulses shown at (c). These pulses are used in order to sample the quantized waveform immediately after each change of level. The resulting pulses, shown at (d), contain all the information necessary for the reconstruction of the quantized television picture, but in order to reduce the bandwidth required for their transmission they must be re-arranged to have uniform spacing, as shown at (e). This results in the need for a separate set of pulses to

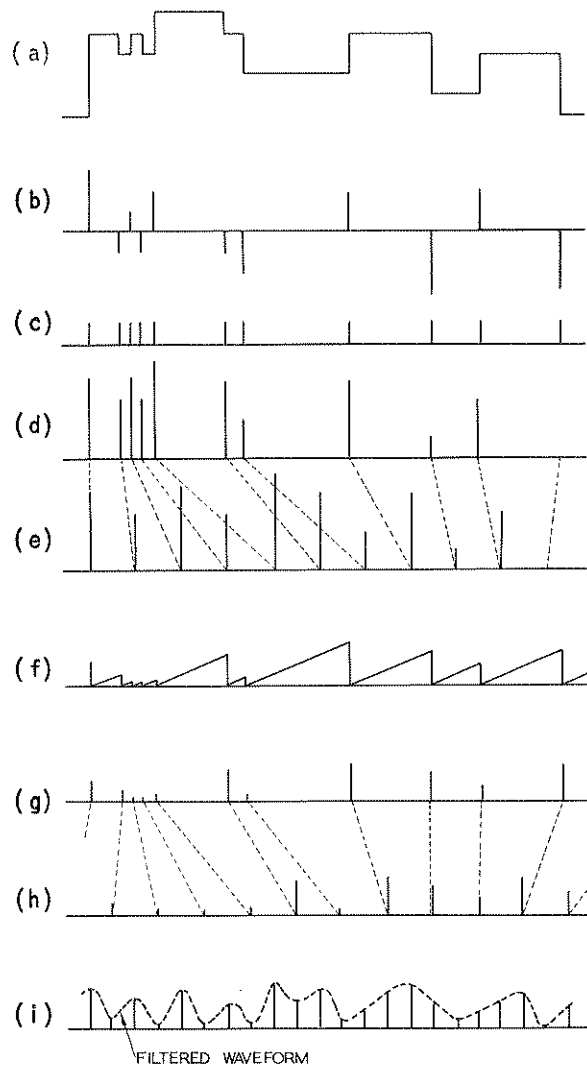


Fig. 2 - Waveforms of "quantized-video" system

- (a) Quantized waveform
- (b) (a) Differentiated
- (c) (b) Full-wave rectified and limited
- (d) Sampled amplitude pulses
- (e) (d) Uniformly spaced
- (f) Sawtooth triggered by (c)
- (g) Position pulses
- (h) (g) Uniformly spaced
- (i) (e) and (h) Interspersed

carry the information necessary for returning the brightness samples to their original spacing. One way of obtaining such information would be to use the uniform-amplitude pulses at (c) to discharge repeatedly a condenser which is being charged at a linear rate. The voltage across such a condenser is shown at (f) and, after differentiation and polarity reversal, shown at (g). The amplitude of each pulse in (g) represents the time interval since the previous pulse. If these pulses are re-arranged to have uniform spacing, as shown at (h), they can be interspersed with the uniformly spaced amplitude pulses (e). The resulting train of pulses, shown at (i), now contains all the information necessary to enable the quantized waveform of (a) to be reconstructed. After passing the final pulse train through an appropriate low-pass filter, the resulting continuous waveform is ready for transmission. At the receiving station the waveform must be re-sampled in order to obtain the two trains of impulses required for the reconstruction of the quantized picture. The bandwidth-reduction factor can be equal to the ratio of the uniform time-spacing between the pulses in the waveform (i) relative to the minimum time-spacing in the waveforms (b) and (c). The system, therefore, allows compression of bandwidth to be achieved only when fewer than half of the picture elements contain significant brightness changes.

The production of the uniformly spaced pulses involves the use of non-uniform-time storage. Each of the two trains of non-uniformly spaced pulses, representing either amplitude or position, must be fed into cells of a storage system and later extracted from the storage cells at a uniform rate. At the receiver the uniformly spaced brightness pulses must again be fed into cells of a third storage system and extracted at a non-uniform rate determined by the position pulses. In order to take advantage of any non-uniform distribution of detail in the vertical direction of a television picture, it may be necessary to store a complete field. In order to obtain a 6:1 reduction of bandwidth, the number of storage cells required in such a system would be at least 10,000 in each of the three stores. This would permit an average number of significant changes of brightness of fifty per line, but in practice more than 10,000 cells would be required in each of the three stores. In the extreme case, where a picture with all its detail confined to the bottom of the field was followed by a picture with all its detail at the top of the field, nearly 17,000 cells might be required in each store in order that cells were always available to accept information as required. Because the position information consists of the intervals between successive brightness changes, errors in the individual position-pulse amplitudes will result in a cumulative error in the position of brightness changes in the reconstructed pictures. It is immediately obvious that if detail in the picture is to be preserved in position to within, say, one half of a picture element relative to the associated detail on the interlaced field, the accumulated error introduced by the storage systems must be less than $\pm \frac{1}{2}$ in, say, 180×600 picture elements, assuming a larger error to be acceptable in the bottom ten per cent of the field. The development of such a storage system would present considerable problems even if digital methods were used, particularly in view of the fact that individual pulses might have amplitudes differing by as much as 500:1. This large ratio could be reduced by arranging that redundant samples were included if any interval between successive brightness changes exceeded, say, 100 picture elements. The inclusion of too many redundant samples would, of course, limit the possible bandwidth saving.

An obvious reduction in the instrumental complexity would result if the number of brightness changes in any one line were limited to fifty. Even allowing

for non-uniform distribution of detail along the line only 100 cells would be required for each of the three stores. Although this simplification has practical advantages, it suffers from the defect that the bandwidth required is determined by the most detailed lines instead of the average line. No advantage can be taken of vertical non-uniformity of picture detail.

In order to compare the two methods of redistribution, it was arranged that the uniform-amplitude pulses, Fig. 2(c), were fed to a system of counters which could be arranged to operate in three different ways. In one condition the counters recorded the number of brightness changes in any picture waveform under examination. In the second condition the counters caused the picture waveform to be switched to zero amplitude when more than a predetermined number of brightness changes had occurred in one field. This had the effect of blacking out a strip at the bottom of the picture, the vertical dimension of the strip being dependent on the amount of detail in the picture. In the third condition the counters caused the blacking out of any line after a predetermined number of brightness changes had occurred since the beginning of that line. This caused black lines to streak in from the right-hand side of the picture as viewed from the front. The extent of these black lines depended on the detail in the particular line. By these means it was possible to measure the bandwidth required to transmit a picture without blacking out any of it, or to assess the effect on a picture of restricting the bandwidth available by use of either redistribution over the whole field or along the line only. The first tests were made using six levels for the grey scale; twelve still pictures produced an average number of 7,000 brightness changes per field. Assuming the ideal of two symbols per cycle of the highest frequency, the average bandwidth was therefore 350 kc/s. The most difficult of the twelve pictures produced 12,000 brightness changes per field, requiring 600 kc/s, but eleven of the twelve pictures required not more than 500 kc/s.

When the number of brightness changes in any one line was restricted to fifty, only four of the twelve pictures were reasonably free of obvious impairment. Some of the pictures required almost 100 changes per line or almost 1 Mc/s of bandwidth. The six-level pictures were subjectively unacceptable. It was found that with moving pictures there was a distracting tendency for portions of moving persons or objects to disappear as the brightness of those portions varied with respect to the immediate background.

Tests were also carried out using thirteen levels for the grey scale. After some experiments, the non-uniform size of step shown in Fig. 3 was chosen for the input/output characteristic of the quantizer. For the twelve slides an average number of brightness changes per field was 12,000, requiring 600 kc/s of bandwidth. The most difficult picture required 900 kc/s and only four of the twelve pictures required less than 500 kc/s.

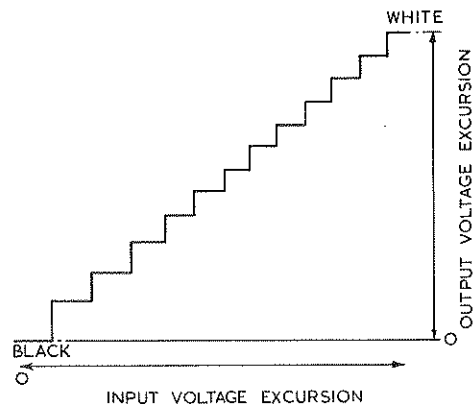


Fig. 3 - Quantizer law for "quantized-video" system

Investigating the possibilities of redistribution in the horizontal direction only, it was found that the majority of the pictures had lines containing more than 100 changes. Restricting the number of changes per line to 100 caused noticeable but possibly acceptable blacking out of parts of the majority of the pictures. One of the twelve pictures was not unduly spoilt by blacking out when the number of changes per line was restricted to fifty.

With the aid of these results we can now estimate the possible saving in channel capacity which would result from the use of this system. The brightness information is contained in thirteen possible levels, and the signal-to-noise ratio must be such that there is virtually no possibility of a level being incorrectly received. This is important because an error in a brightness level would exist not merely for the duration of one picture element, but would continue until the next brightness change occurred. This would result in obvious streaks of incorrect brightness lasting up to the maximum permitted interval between brightness changes. The peak noise must therefore be less than one twenty-sixth of the peak brightness signal. Accepting that the virtual peak is five times the r.m.s. value of noise, we require a ratio of peak-signal to r.m.s.-noise of 42 dB. It must be remembered that this ratio is required in a bandwidth of 500 kc/s or less, assuming redistribution over a complete field. Thus, the brightness information requires a channel capacity of approximately one quarter of that required for the entire original signal.

The signal-to-noise ratio required for the position information in the system using redistribution over the field can be estimated as follows. If the accumulated r.m.s. error of position is to be restricted to less than half the duration of a picture element ($0.083 \mu s$) at the lower part of the picture, say after 180 lines with an average of ninety intervals per line, the r.m.s. error per interval must be restricted to one part in $(2\sqrt{180 \cdot 90})$, or $4 \cdot 10^{-3}$ of one picture element duration. The longest interval permitted has a duration equal to 500 picture elements, corresponding to the active portion of one line, and the required signal-to-noise ratio would be 102 dB. This impossible figure could be reduced to 74 dB by limiting the maximum interval to twenty picture elements ($3.3 \mu s$). This could be achieved by arranging that whenever a period of $3.3 \mu s$ elapses without a brightness change an extra sampling pulse is added to the pulse train of Fig. 2(c). This is, of course, adding redundant information but from experimental results it appears that the increase in the number of pulses is small.

A more realistic requirement for the signal-to-noise ratio might be achieved by quantizing the intervals into integral numbers of picture-element durations. This time-quantization, which could be done by synchronizing the sampling pulses to a pulse train having a 6 Mc/s repetition rate, would also be necessary for digital storage of the position information. If the peak noise is restricted to be less than half the amplitude representing one picture-element duration it should be possible, by means of amplitude-gating circuits, to measure correctly each interval. In this case the required signal-to-noise ratio would be $(2 \times 20):1$. Allowing a factor of 5:1 as the ratio between the virtual peak and the r.m.s. value of noise, the required peak-signal to r.m.s.-noise ratio would be 46 dB. This same figure would apply in the case of line storage. The 42 dB signal-to-noise ratio for the brightness information and the 46 dB ratio for the position information are each required in a bandwidth of 500 kc/s or less. The transmitter power required would be the same as would be necessary for ratios of 34 dB and 38 dB respectively in a bandwidth of 3 Mc/s.

If the position signal had to be capable of being transmitted over a channel having only the 30 dB signal-to-noise ratio which we have assumed adequate for a conventional video signal, then the maximum interval between sampling pulses would have to be restricted to about four picture elements. Redundant pulses would then constitute a much higher proportion of the total number of pulses, and the bandwidth compression could never exceed 2:1, even this figure being attained only in the limiting case of a uniformly illuminated screen.

From these figures we can say that the brightness and position signals could each be transmitted in a bandwidth equal to one-sixth of the original 3 Mc/s bandwidth but would each require a greater transmitter power than would the original conventional signal; the brightness information would require a peak power some 4 dB greater, while the position signal would require 8 dB more peak power.

It must be stressed that the system so far described does not fully utilize the possibilities offered by statistical coding. The various possible brightness levels are not necessarily of equal probability of occurrence. Similarly, some interval lengths are more frequent in occurrence than others. It is of interest to calculate the possible saving in channel capacity which might result from the use of a code to remove this redundancy. This redundancy can be computed by subtracting the entropy for the practical distribution of signal amplitudes from the entropy for a system in which all the signal amplitudes are equally probable.

$$R = \log_2 n - \sum_{i=1}^n P(i) \log_2 P(i) \quad (3)$$

where R = the redundancy in bits/symbol
 n = the number of possible amplitudes
 $P(i)$ = the probability of the i th amplitude

Fig. 4 shows the plotted distributions of the amplitudes of position pulses for four

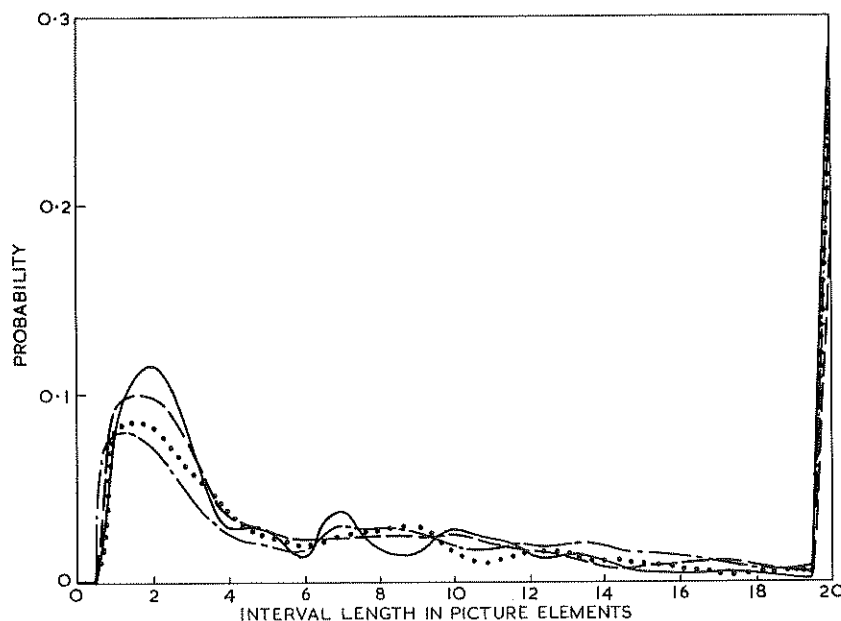


Fig. 4. Frequency distribution of interval length for "quantized-video" system

different pictures, comprising a close-up of a girl, a full-length portrait of a girl, a group of people and a street scene. These distributions have been modified by restricting the maximum interval between brightness changes to a twenty picture-element duration, or $3.3\mu\text{s}$. This causes the peaks at the right-hand end of the curves. These distributions are so similar that we can take the average. The redundancy, as defined by Equation (3) and computed from the average of the distributions shown in Fig. 4, is just less than 1 bit/symbol. This means a theoretical possible reduction in the required signal-to-noise ratio of nearly 6 dB for the position signal, although there is little hope of obtaining this benefit in practice.

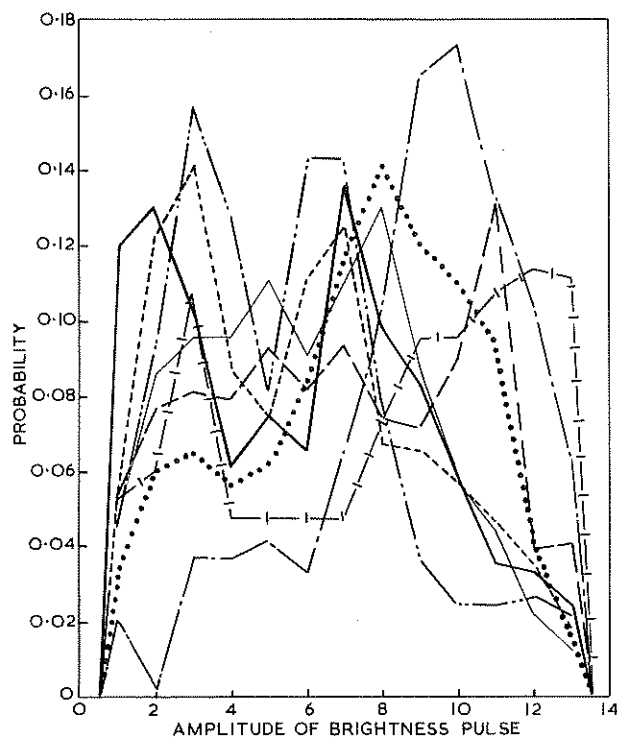


Fig. 5 - Frequency distribution of brightness-pulse amplitude for eight different still pictures ("quantized-video" system)

Fig. 5 shows the probability distributions of the different brightness-pulse amplitudes for eight still pictures including the four used for Fig. 4 with the addition of two more close-ups, one male and one female, a landscape and a seascape. The maximum redundancy in these distributions is less than 0.4 bit/symbol; this would permit a saving of 2 dB in the required signal-to-noise ratio. In order to take advantage of this redundancy, the code used would need to be changed as the picture content changed. As Fig. 5 shows, the average distribution for all eight pictures is very uniform and a code suitable for all eight pictures would only be able to remove a redundancy of less than 0.05 bit/symbol. The effect of adding the redundant pulses by restricting the maximum interval to twenty picture elements, as discussed above, is negligible.

From these considerations it is possible to state that the "quantized-video" system might be capable of reducing the bandwidth required for a thirteen-level 405-line picture to 1 Mc/s with a somewhat increased transmitter power. At this stage it is pertinent to ask how such pictures would compare with pictures produced by passing the original video waveform through a 1 Mc/s low-pass filter. Subjective comparisons were made between pictures produced by the two methods, and displayed on identical 21 in (53 cm) monitors standing side by side. The observers, in groups of five at a time, sat at distances from the monitors of between four and eight times the picture height and each observer was asked to indicate by means of a silent-operating switch when he or she thought that the quantized picture was preferable to the other picture. The reason for requiring that the quantized picture should be preferable and not merely equal to the other picture is that unless it were markedly

superior its adoption would be ruled out by its considerably more difficult instrumentation and greater required transmitter power.

The quantized pictures shown in the tests were comparable with, or superior to, any likely to be obtained with a fully instrumented system because of the freedom from positional errors which could, in practice, be caused by excessive noise added to the coded signal, and by imperfections in a practical storage and coding system. The quantized pictures were shown without restricting the number of brightness changes in any line or field. The picture sources were a $3\frac{1}{4} \times 3\frac{1}{4}$ in (82.6×82.6 mm) flying-spot slide scanner and a 35 mm telecine unit. These sources produced pictures with very good signal-to-noise ratios, and good definition up to a bandwidth of 3 Mc/s.

The picture obtained with a 1 Mc/s low-pass filter was crispened⁶ by adding to the video waveform a second waveform obtained from the time-derivative of the first. This had the effect of sharpening the edges and details in the picture. It is not, of course, possible by such means to restore details removed by the low-pass filter, but sharpening the edges produces a subjective impression of increased bandwidth.

These comparisons were performed by twenty-five observers of whom ten were technical personnel engaged on television work and fifteen were non-technical. Thirteen slides were used and six of these were preferred in the quantized form by more than 50 per cent of the technical observers but only four of these same slides were preferred in quantized form by more than 50 per cent of non-technical observers. The average preferences for the quantized pictures were 45 per cent and 30 per cent for the technical and non-technical observers respectively.

Further tests were made using motion-picture film which lasted seven minutes and consisted of short sequences of various types of scene, i.e. flood scenes, cycle racing, car rally, embarkation of troops, boxing match. The result of the test using non-technical observers was a 10 per cent preference for the quantized pictures, but the technical observers showed a 33 per cent preference for the quantized pictures.

Fig. 6 shows photographs taken from the monitors of one of the still pictures used in the tests. Fig. 6(a) shows the 13-level quantized picture; photographic reproduction has reduced the number of levels visible but Fig. 6(b) shows the locations of brightness changes, all of which are easily visible in a television picture having a peak brightness of 15 ft-L with an ambient lighting of 0.5 ft-L. Fig. 7 shows the crispened picture obtained using the 1 Mc/s low-pass filter.

It was generally agreed that although 13 levels are adequate for areas of pictures containing detail with medium to high contrast, areas containing low-contrast detail and gradual changes require considerably more than 13 levels for realistic reproduction. The texture of materials requires more than 13 levels, otherwise all cloths look like satin with smooth areas of uniform brightness separated by hard edges.

Further tests were carried out with the quantized pictures modified in a manner proposed by Cutler.⁷ The 13 levels at which even fields were quantized were displaced by one half quantum with respect to the levels used for the odd fields. By this means the complete picture can contain 25 levels, although each field only contains 13 levels. If the video waveform is quantized into equal-amplitude steps the modification is easily instrumented. Before quantization the video waveform has

(a)



(b)

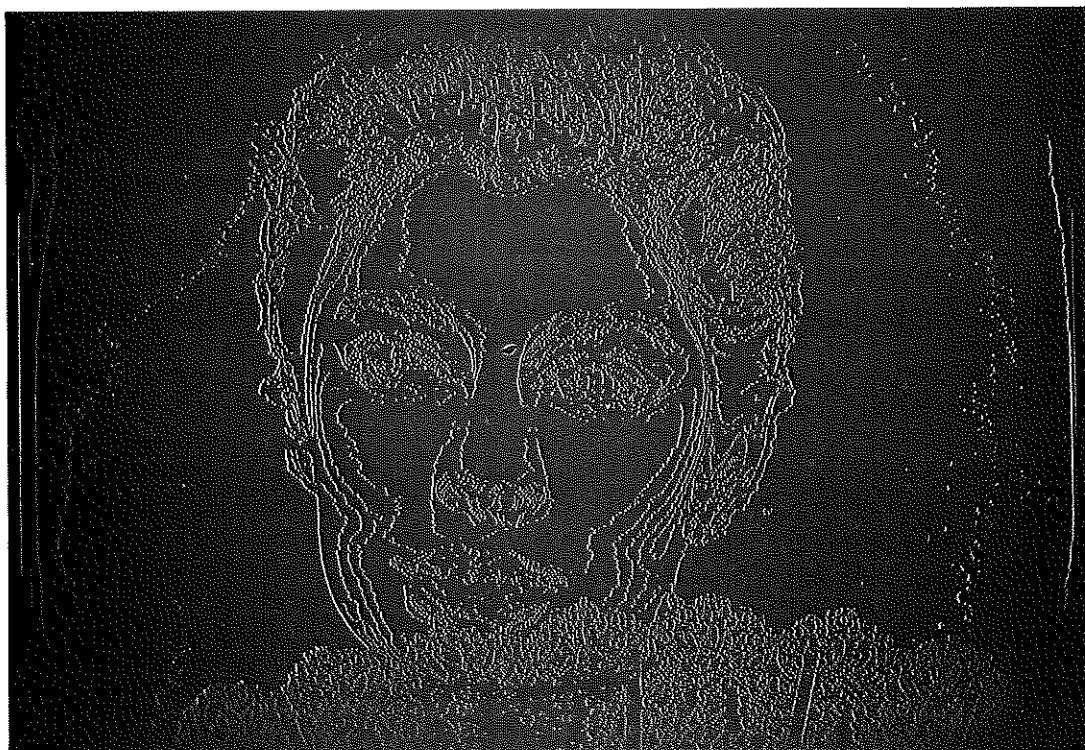


Fig. 6 - Pictures obtained with "quantized-video" system

(a) Thirteen-level quantized picture

(b) Positions of brightness changes



Fig. 7 - Picture obtained with 1 Mc/s filter and crispener

added to it a square wave such that alternate fields are displaced by a voltage equal to half of one quantum. The quantized waveform will then consist only of 13 levels but the contours of these levels will be different in consecutive fields. The addition, at the receiver output, of a square wave with amplitude equal to half of one quantum, and in phase opposition with respect to that added originally, will so displace alternate fields that the reconstituted picture will contain 25 levels. This will not increase the bandwidth or channel capacity required because only 13 brightness levels are transmitted, the levels being assigned different brightnesses at the receiver according to the pre-arranged choice of odd or even field. The system has the disadvantage that a 25 c/s brightness flicker is introduced, although consecutive brightness levels flicker in phase opposition.

Fig. 8 illustrates the principle of the system; for simplification the input waveform is represented by a repetitive sawtooth waveform which, with an added square wave, is shown at (a) with the quantizing levels marked. The 4-level quantized waveform is shown at (b). The effect of adding the square wave (c) and superimposing consecutive waveforms is shown at (d). This shows that 7 levels are present in the final stage although only 4 are transmitted. This provides a closer representation of the original sawtooth, but some levels are brighter during odd fields (solid-line waveform), and the others are brighter during even fields (dotted-line waveform). Thus these areas will flicker in phase opposition, so that, if the areas involved are small, the resultant effect can be quite acceptable. In large areas, however, the 25 c/s flicker is unpleasant. Subjective tests failed to show a

material increase in the acceptability of the quantized pictures when the modification was adopted.

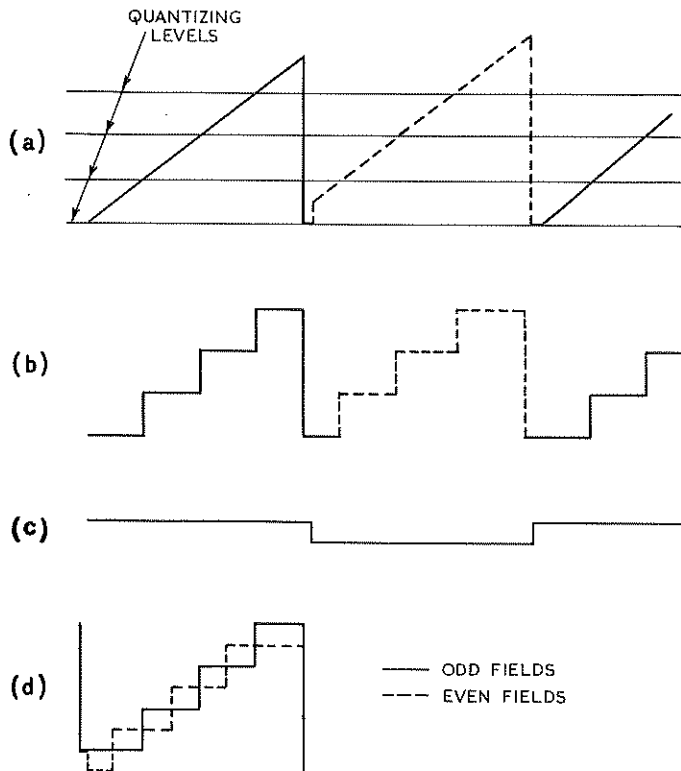


Fig. 8 - Effect of adding square wave to increase number of levels in superposed waveforms

- (a) Sawtooth with half-quantum square wave added
- (b) Quantized waveform
- (c) Square wave to be added at receiver
- (d) Superposition of alternate sawteeth showing effectively seven levels

4. THE "QUANTIZED-HIGHS" SYSTEM

This system is an attempt to improve the appearance of the reconstituted pictures by removing the necessity to quantize those parts where the brightness changes gradually with position. This removes the contour lines in areas with no detail. It is achieved by removing from the input waveform a narrow band of frequencies at the low-frequency end of the spectrum. These low-frequency components are transmitted without being quantized. The remainder of the picture waveform can be quantized into a number of discrete levels of amplitude, then converted into position and brightness pulses and bandwidth-compressed in the same manner as was described for the "quantized-video" system. Two channels would be required for the "quantized-highs" system, one for the transmission of the unmodified low-frequency component and the other for the bandwidth-compressed "highs" signal. At the receiver the "highs" signal would require to be decoded and reconstituted before being added to the low-frequency signal in order to simulate the original video waveform.

For the investigation into this system the input waveform was passed through a low-pass filter in order to obtain the "lows" component which was then subtracted from the input waveform, suitably delayed in time, and so produced the "highs" waveform. This was quantized into thirteen levels, the centre level being zero

amplitude with six positive levels and six negative levels. The two component waveforms were added and displayed on a 21 in (53 cm) picture monitor for the subjective tests. The quantized "highs" waveform was also differentiated with respect to time, full-wave rectified and limited in amplitude to provide the transition pulses for operating the counter circuits. These circuits were again used to count the number of pulses per second, thus enabling the required bandwidth to be computed, and also to simulate the effect of bandwidth restriction assuming storage capacity suitable either for redistribution over a complete field or in the horizontal direction only. When the "highs" signal was suppressed, because the number of pulses had reached the permitted maximum, the "lows" component remained visible, thus avoiding the sudden change of brightness which occurred with the "quantized-video" system.

Two alternative low-pass filters were used in the investigation. One had nearly uniform amplitude and group-delay characteristics up to the cut-off frequency of 100 kc/s and then an extremely rapid increase of attenuation with increasing frequency. The filter included delay-equalizing sections and had an impulse response approximating to a $(\sin x)/x$ function. The other filter had a near-Gaussian amplitude/frequency response, being 3 dB down at 150 kc/s and 14 dB down at 300 kc/s. Fig. 9 shows the type of frequency response (a) obtained with the sharp-cut filter and, at (c) and (d) respectively, the "lows" and "highs" waveforms for a step-function input (b). Fig. 10 shows the same information for the other filter. These figures illustrate the oscillatory nature of the waveforms produced by the sharp-cut filter.

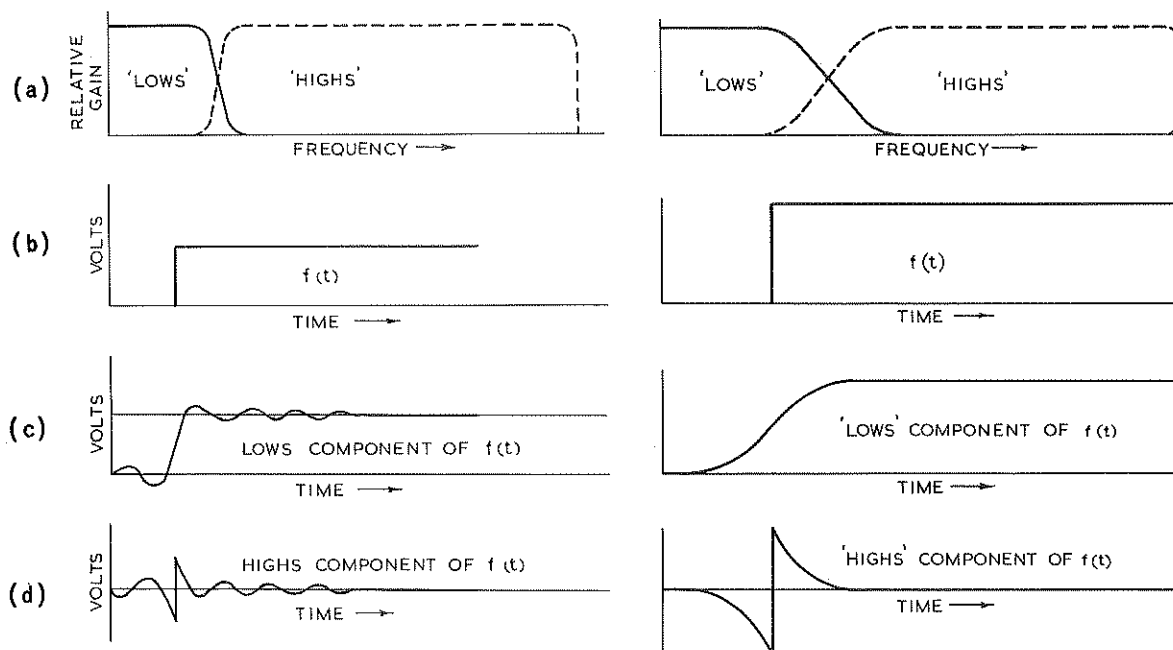


Fig. 9 - Sharp-cut frequency-division with resulting waveforms for a step time function

Fig. 10 - "Gaussian" frequency-division with resulting waveforms for a step time function

Tests made with the two filters showed that in general the extra bandwidth required for the "highs" signal produced with the sharp-cut filter more than compensated for the smaller bandwidth required for the "lows" signal. Fig. 11 shows



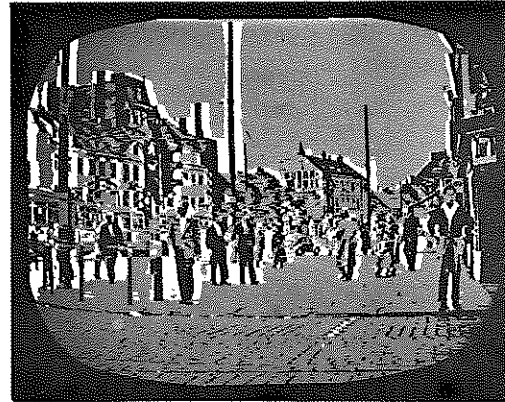
(a)



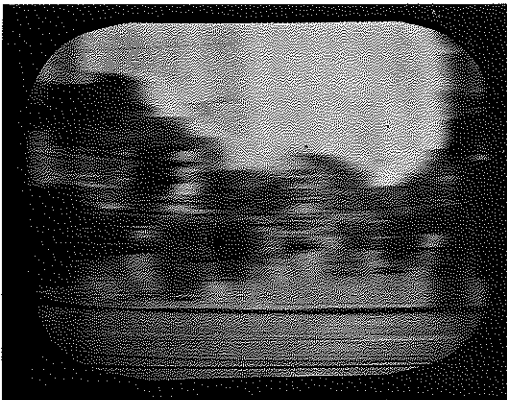
(d)



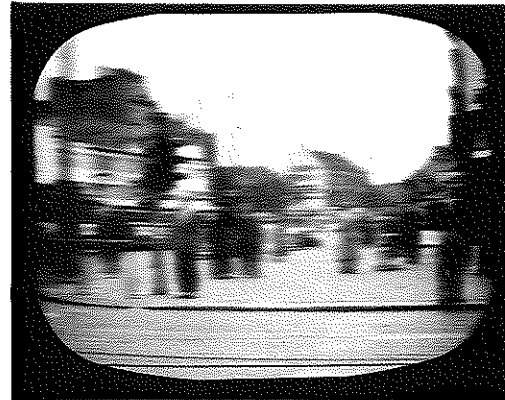
(b)



(e)



(c)



(f)

Fig. 11 - Pictures obtained with "quantized-highs" system

- (a) Composite picture using 100 kc/s sharp-cut filter
- (b) Quantized "highs" using 100 kc/s sharp-cut filter
- (c) "Lows" using 100 kc/s sharp-cut filter
- (d) Composite picture using 300 kc/s "Gaussian" filter
- (e) Quantized "highs" using 300 kc/s "Gaussian" filter
- (f) "Lows" using 300 kc/s "Gaussian" filter

photographs of the "lows", quantized "highs" and the reconstituted picture for both the filters. The bandwidths required for these pictures would be approximately the same, 100 kc/s and 800 kc/s for the sharp-cut filter and 300 kc/s plus 600 kc/s for the other filter.

The tests showed that, with redistribution over a complete field, a total bandwidth of 1 Mc/s would be required to produce acceptable pictures with the "quantized-highs" system. Only two of the thirteen slides tested were capable of being transmitted through less than 1 Mc/s without some portion of the picture being marred by suppression of the "highs" signal. One of the slides required about 1.3 Mc/s for acceptable picture quality. Of these bandwidths a band of between 40 and 80 kc/s was required for the "redundant" pulses resulting from the restriction of the maximum interval duration to $3.3 \mu\text{s}$. This apparently wasted bandwidth is, in fact, a worthwhile exchange for the reduction of the alphabet required for the position-pulse amplitudes. Assuming, as in the "quantized-video" case, that intervals must be correct to within one half of a picture-element duration, the reduction of the maximum interval from 500 to 20 picture elements results in a reduction from 10 to 5.3 bits/symbol.

The measurements show that in order to reproduce the majority of pictures without obvious and unacceptable defects the system must be capable of an average of seventy-five edge pulses per line. This would require a bandwidth of 750 kc/s for the "highs" signal in addition to the 300 kc/s for the "lows" signal. In order that noise shall not introduce positional error, the peak-position-signal to r.m.s.-noise ratio must be 46 dB. The brightness signal requires a peak-signal to r.m.s.-noise ratio of 42 dB. The "lows" signal would probably require a signal-to-noise ratio of 40 dB because this is the ratio which would result if the normal 3 Mc/s bandwidth for a 30 dB signal-to-noise ratio were reduced to 300 kc/s. Therefore, assuming redistribution over a field, the bandwidth required is around 1 Mc/s as compared with the original 3 Mc/s, but each of the three component signals requires a transmitter power equal to or in excess of that required for the complete signal in the conventional system.

Investigation of the amplitudes of the brightness and position pulses shows a non-uniformity of probability of occurrence which suggests a further possible saving amounting to 1 bit/symbol in the case of the position signal and less than 0.5 bit/symbol for the brightness signal. Thus it is theoretically possible that a signal-to-noise ratio of some 40 dB would be sufficient for each of the three component signals. This would result in the "quantized-highs" system providing a 3:1 bandwidth reduction with a 3:1 increase in the required peak transmitter power. The picture quality obtainable with this system, although better than would be obtained with the "quantized-video" system, was noticeably inferior to that of the original picture. The pictures produced by the "quantized-highs" system were not compared subjectively with the pictures produced by passing the original waveform through a 1 Mc/s low-pass filter. It was found that for a given picture quality the bandwidth required by the "quantized-highs" system was about twenty per cent greater than that required by the third system, the "synthetic-highs" system which will be described in Section 5.

Tests were carried out to examine the effect of modifying the "quantized-highs" signal by changing the levels of quantization in successive fields as described

for the "quantized-video" system. The result was a considerable reduction of the visibility of the unwanted contours produced by the quantizing of the "highs" signal. The number of levels available for this signal was, of course, increased from ± 6 to ± 11 . The 25 c/s flicker introduced by this modification was confined to the "highs" signal and therefore to small areas of the picture. This made the flicker much less annoying than in the "quantized-video" case. It was thought that this modification resulted in a worthwhile improvement in the reproduced picture quality. For a given picture quality it was estimated that the modification permitted a bandwidth reduction of about ten per cent or 100 kc/s.

5. THE "SYNTHETIC-HIGHS" SYSTEM

This system differs from the "quantized-highs" system only in the manner of obtaining and reproducing the high-frequency information. The low-frequency component, obtained by passing the video waveform through a low-pass filter, is transmitted unmodified and added to the reconstructed "highs" signal at the receiver. The high-frequency information consists only of edges and is obtained by differentiating, with respect to time, the input video waveform. This derivative is then quantized into a few discrete amplitude levels so as to reduce the required alphabet for the "highs" signal. Adjustment of the smallest level in the quantized signal enables the low-frequency components of the derivative to be eliminated because they will have relatively smaller amplitudes.

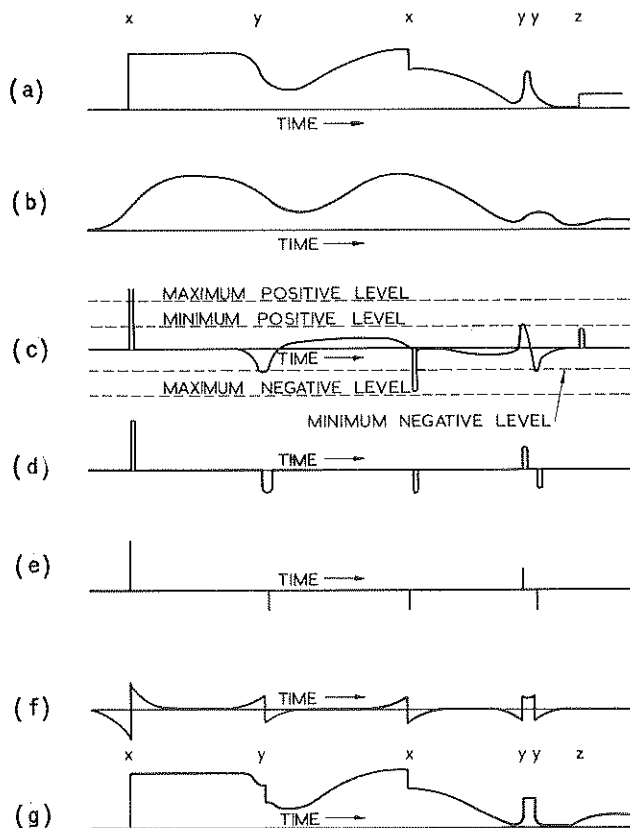


Fig. 12 - Waveforms of "synthetic-highs" system

- (a) Video input
- (b) "Lows"
- (c) Derivative of (a)
- (d) Quantized derivative
- (e) Brightness pulses for "highs" after decoding at receiver
- (f) "Synthetic highs"
- (g) Final waveform (b)+(f)

Fig. 12 shows approximate sketches of the waveforms encountered in the system. The input video waveform is represented by (a) and the "lows" waveform obtained with the low-pass filter having a monotonic response is shown at (b). The time-derivative of (a) is shown at (c) and, after quantizing, at (d). The pulses in this waveform have various durations. The system depends, however, on each edge being defined only by its position and by its amplitude. A pulse of long duration must therefore be converted either to a single pulse of the standard shape or into several standard pulses in succession. We shall here consider only the first of these alternatives, although we shall deal with the second alternative later.

In a practical system the waveform shown in Fig. 12(d) would be converted into two sets of regularly spaced pulses, one representing the amplitudes of the pulses in waveform (d) and the other the intervals between them. These uniformly spaced pulses can be passed through a suitable low-pass filter and transmitted in the same manner as described for the other systems. At the receiver the "highs" signal will require to be sampled and decoded to produce the waveform shown at (e). This waveform is passed through a transversal filter in order to produce the specially shaped "synthetic-highs" waveform shown at (f). The shaping filter consists of a length of delay-line fed from a matched source-impedance and terminated in a short circuit. The line is tapped at small regular intervals along its length. The outputs from these taps are added together to produce the shaped "highs" waveform. The signal amplitude provided by each tap is inversely proportional to the distance between the tap and the short-circuited end of the line. Thus if a pulse is fed into the line the output consists of pulses of progressively increasing amplitude as the input pulse approaches the end of the delay-line. After reflection at the short circuit the pulse is reversed in polarity and the output consists of pulses with inverted polarity and diminishing amplitude with increasing time. After being filtered and polarity reversed the waveform is as shown at (f), and the result of adding this to the "lows" waveform is shown at (g).

Comparison of the waveforms in Fig. 12(a) and (g) illustrates some of the system characteristics. The points marked x represent sharp edges of sufficient amplitude and are reproduced quite well. The points marked y are more gradual edges and are reproduced as sharp edges. The point marked z is a sharp edge of too small an amplitude and is reproduced only by the low-frequency component. The system provides a representation of low-frequency components, and sharp edges of sufficient amplitude. Less sharp edges, if of sufficient amplitude, are reproduced as sharp edges. This undesirable feature can be minimized, however, by sampling the quantized derivative of the video signal at a 6 Mc/s rate. A pulse of relatively long duration, denoting the presence of an edge of moderate sharpness, then becomes a succession of standard pulses. When these are applied to the shaping filter the outputs due to the individual pulses overlap. Thus the resultant waveform is more gradual than the waveform produced by a single pulse and allows the original edge to be reproduced more accurately. In a practical system such a sampling process would in fact be necessary, for the reasons outlined in the discussion on the "quantized-video" system. The extra pulses necessary to achieve this subjective improvement will, of course, require extra bandwidth.

In the experiments to be described no attempt was made to make all pulses of the same shape. Less sharp edges were therefore reproduced as such, because they generated pulses of longer duration which in turn gave more gradual transitions when

passed through the shaping filter. The picture quality was thus comparable to that obtained by using several pulses to describe each moderately sharp edge. The counting circuits, however, only registered each pulse once, irrespective of its duration. As a result of this procedure the quality of the pictures was probably better than would actually be obtainable in the bandwidths estimated.



(a)



(b)



(c)



(d)

Fig. 13 - Pictures obtained with "synthetic-highs" system

- (a) "Lows"
- (b) Quantized derivative of original waveform
- (c) "Synthetic-highs" obtained by shaping (b)
- (d) Composite picture obtained by adding waveforms of (a) and (c)

Fig. 13 consists of photographs of displayed components of a picture produced by the "synthetic-highs" system. Fig. 13(a) shows the "Lows" waveform obtained with the low-pass filter with the gradual attenuation/frequency characteristic. Fig. 13(b) shows the quantized time-derivative of the incoming picture. Fig. 13(c) shows the result of "shaping" the waveform shown in 13(b). Fig. 13(d) shows the result of adding the waveforms of pictures 13(a) and 13(c). Measurements made with the thirteen test slides showed that twelve of them could be reproduced reasonably well with an average number of seventy edges per line. If, by means of

non-uniform time-storage, these edges could be redistributed over a complete field the bandwidth required for these pictures would be 1 Mc/s, of which 700 kc/s would be required for the "highs" signal. The exception to this required an extra 100 kc/s but the two most simple of the slides required an average of fifty edges per line and therefore an overall bandwidth of 800 kc/s. Of the thirteen slides, six had many lines containing more than seventy edges in each and three slides had many lines containing more than 100 in each. Therefore, in a practical system with storage facilities permitting redistribution only along each line, bandwidth of 1 Mc/s, with 700 kc/s allocated to the "highs" signal, would not be sufficient to reproduce more than seven of the thirteen slides without loss of detail in some areas of the picture. In order to determine whether such pictures would be acceptable, tests were carried out in which twenty-five people made subjective comparisons between pictures obtained with the "synthetic-highs" system and similar pictures obtained with a 1 Mc/s low-pass filter and crispener circuit.

The subjective tests were made with the two pictures displayed simultaneously on 21 in (53 cm) monitors. Each observer recorded his or her opinion as to whether or not the picture obtained with the "synthetic-highs" system was preferable to the similar picture obtained with a 1 Mc/s low-pass filter and crispener circuit. As stated earlier, this method of assessment was felt to be justified by the fact that one would not decide to develop the more complex of two systems unless it produced pictures significantly better than the simpler system.

The comparisons were made with thirteen still pictures obtained from a $3\frac{1}{4} \times 3\frac{1}{4}$ in (82.6 x 82.6 mm) flying-spot slide scanner, and forty-five excerpts of moving pictures from a 35 mm telecine apparatus. The results obtained when redistribution over a complete field was simulated were that 80 per cent of comparisons favoured the "synthetic-highs" system with still pictures. This figure fell to 40 per cent for motion pictures.

The tests were repeated with the maximum number of edges restricted to seventy in any one line. "Synthetic-highs" system pictures were preferred in 30 per cent of comparisons with still pictures and 20 per cent with motion pictures.

A small amount of experimental work was carried out to examine the possibility of changing the input/output amplitude-characteristic of the quantizer and so obtain an optimum as regards picture quality and bandwidth reduction. The three characteristics shown in Fig. 14 were tried. In Fig. 14(a) the excursion of the input voltage from zero to each of the first thresholds is only one half the voltage difference between the other adjacent thresholds. This represents an attempt to include as much small amplitude detail as possible without requiring too large a number of levels. Fig. 14(b) shows an extension of this principle in which the coarseness of quantizing is proportional to the amplitude of the detail. This characteristic requires only seven levels as compared to thirteen levels in the first characteristic tried. This represents a saving of almost 1 bit/symbol for the brightness information of the "highs" component, but the result was noticeably inferior as regards picture quality. This in general was due to the fact that if the "highs" component of an edge is not accurately matched in amplitude to the "lows" component a horizontal streak is apparent on each side of the edge. This results in a somewhat smeared picture. For this reason, the finer the gradation of the quantizer

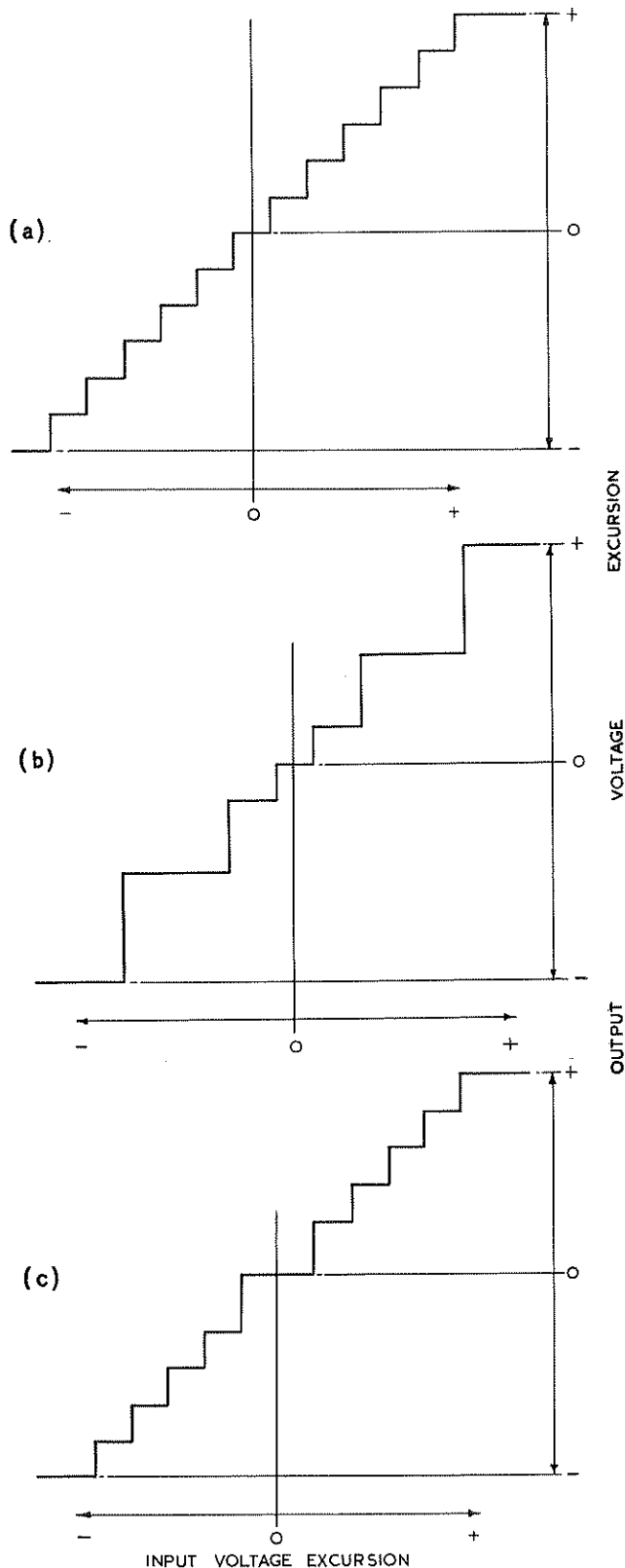


Fig. 14 - Quantizer laws for "synthetic-highs" system

characteristic the better is the appearance of the final picture. The characteristic shown in Fig. 14(c) provides a good performance as regards the matching of the "highs" and "lows" amplitudes and the inclusion of small-amplitude detail without wasting too many of the available edge pulses in reproducing noise in the original picture. This was found to be particularly effective when dealing with relatively noisy picture sources. The channel-capacity requirements for the "synthetic-highs" system were about the same as for the "quantized-highs" system. A bandwidth of about 1 Mc/s, of which 300 kc/s would be required for the low-frequency component with a peak-signal to r.m.s.-noise ratio of 40 dB, would leave 350 kc/s for the "highs" brightness information with, say, 42 dB signal-to-noise ratio and 350 kc/s for the position information with, say, 46 dB signal-to-noise ratio. These figures include the redundant pulses added to reduce the maximum interval to twenty picture elements.

Fig. 15 shows the distribution of frequency of occurrence plotted against amplitude of the brightness pulses for the sum of six slides. Computation of the entropy associated with this distribution reveals a redundancy of about 0.8 bit/symbol. If a statistical code were developed to take advantage of this redundancy the signal-to-noise ratio could probably be reduced to less than 40 dB for the brightness information.

Fig. 16 shows a similar distribution for the position pulses. The redundancy in this distribution is about 0.5 bit/symbol and, by means of a suitable code, it might be possible to reduce the signal-to-noise ratio required for the position

information to 43 dB. By these means a bandwidth saving of 3:1 could be achieved with a channel-capacity saving of about 2:1. In order that the resulting picture quality should have an advantage over the picture quality obtained with a 1 Mc/s low-pass filter, it would be necessary to include means for redistribution of the edge information over a complete field.

6. DISCUSSION OF RESULTS

The investigation has shown that, although the three systems examined could be used to reproduce television pictures in a bandwidth of about 1 Mc/s, they would each require a much greater transmitter power than that required by the conventional system. The saving in channel capacity which would result from the use of any of these systems might be as much as fifty per cent, but this saving is not entirely due to a reduction in the redundancy inherent in the conventional system. It is largely due to a reduced accuracy of reproduction of the original pictures. In fact, when the reproduced pictures were compared with those obtained after reducing the bandwidth of the

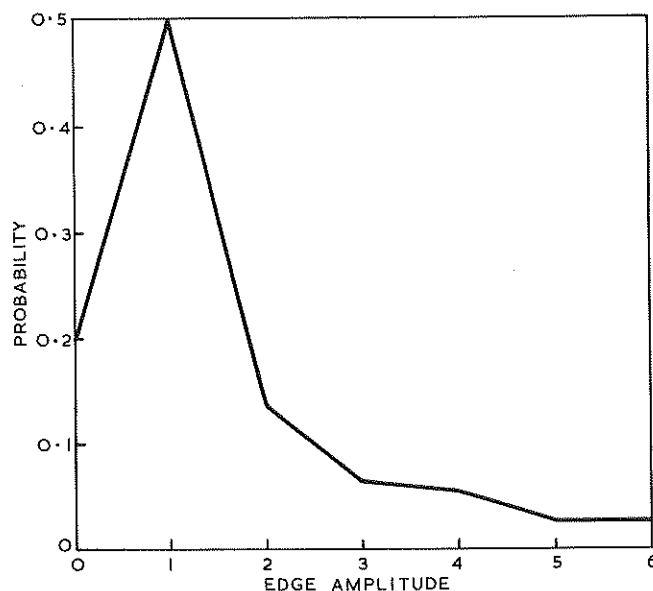


Fig. 15 - Frequency distribution of edge amplitude for "synthetic-highs" system

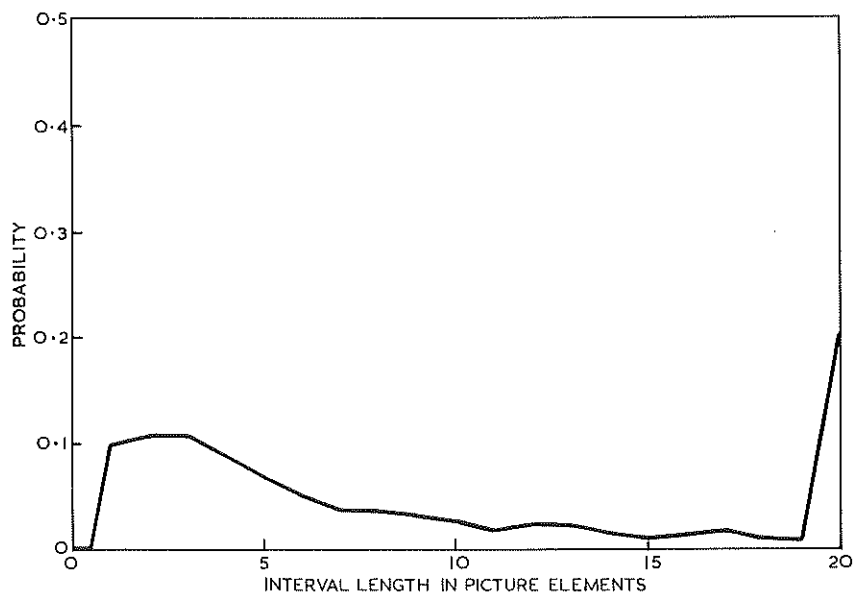


Fig. 16 - Frequency distribution of interval length for "synthetic-highs" system

conventional system by means of a 1 Mc/s low-pass filter and a simple crispener circuit, none of the three systems showed any significant superiority.

Measurements made during the investigation show why the systems proved less effective than was hoped.

The principle of transmitting the amplitude and position of brightness changes instead of transmitting the brightness of every picture element, as in the conventional system, can lead to a useful bandwidth reduction only if the number of brightness changes is considerably less than the number of picture elements. In a single field of a 405-line television picture there are approximately 100,000 picture elements, but it is generally agreed that no more than 200 brightness levels could be distinguished in even the highest quality of transmitted television pictures. Because there are more possible values for the position signal than for the brightness signal, the former will require a larger signal-to-noise ratio. This increase is exaggerated by the need for a greater freedom from random error in the case of the positional information. The human eye is capable of integrating the random changes of brightness level in small areas to such an extent that one can easily distinguish between adjacent brightnesses even when the amplitude of the difference is smaller than the r.m.s. value of the random changes caused by noise. There does not appear to be a similar tolerance to random change of position which produces the effect of "blurring" or loss of fine detail. Teer⁶ has shown that the r.m.s. error of position must be kept as low as one fifth of the time of duration of a picture element. The signal-to-noise ratio required for a position signal can be reduced by methods discussed in this report, i.e., transmitting not position, but the interval between changes of brightness, and restricting the maximum interval by including "redundant" sampling pulses. In spite of this, the signal-to-noise ratio required is greater than that required for brightness. In addition to the need for a greater signal-to-noise ratio for the position signals in the three systems investigated, the brightness signals will also require a signal-to-noise ratio greater than that necessary for the conventional system. Because the number of permitted brightness changes is considerably smaller than the number permitted in the conventional system the average duration, or length along the line, of noise "spikes" must be considerably longer than the picture-element duration of noise "spikes" in the conventional system. In the "quantized-video" and "quantized-highs" systems the duration of the brightness change caused by a noise peak can last for up to the maximum of, say, twenty-picture-element duration. In the "synthetic-highs" system the noise peaks will be extended in duration by the shaping filter to have a duration of many picture elements. These increases in duration will increase the visibility and so raise the need for a better signal-to-noise ratio for a given visibility.

These requirements for an increased signal-to-noise ratio can easily be satisfied provided the bandwidth of the new signal is sufficiently small. If the signal-to-noise ratio required were, say, 6 dB greater than the 30 dB we have taken as the value for the conventional system, the bandwidth would have to be reduced to one quarter if the same peak transmitter power were to be used. This bandwidth reduction could be achieved if the number of brightness changes in each line were restricted to a maximum of seventy-five for the "quantized-video" system and about fifty for the other two systems. These numbers are based on the assumption that redistribution of picture detail is only possible in the horizontal direction. If redistribution over a complete field is possible, the maximum numbers in any field would be about 15,000

and 10,000 respectively. If under these conditions the reproduced pictures were of comparable quality to those obtainable with the conventional systems, a 4:1 bandwidth reduction, and a 3:3:1 reduction of required channel capacity, could be claimed. Unfortunately the investigation showed that even when the bandwidth was one third and the channel capacity one half of that required by the conventional system, the picture quality was noticeably inferior to that representative of normal television.

The measurements showed that the number of brightness changes required for acceptable picture quality was much greater than had been expected. It must be remembered that, if a compression system is to compete with the conventional system, it must be capable of reproducing satisfactorily most of the pictures normally seen on television. It will not be sufficient that it is capable of transmitting the "average" picture or even, say, one half of the pictures which may reasonably be expected to be transmitted.

The subjective tests show that the picture quality obtained with the systems examined was less acceptable with motion pictures than with slides. No investigation was made to find the reason for this, but it may be due to the changing position of defects as the picture content changes. Incomplete edges, or contours showing discontinuities of brightness, become much more obtrusive when they are continually changing than when they are stationary. The bandwidth-limited pictures sometimes contain small areas in which the detail has been suppressed or in which the picture content has been blacked out. If these areas are continually changing shape or position they become more distracting.

There is, of course, the need for a system capable of transmitting, with a reduced bandwidth, pictures of reduced quality on occasions when the pictures may have sufficient topical interest. Comparison of the pictures produced by the three systems, with similar pictures produced in the same bandwidth by the conventional system, led to the conclusion that even in these circumstances the extra complexity of the new systems is hardly likely to be worthwhile. The possibilities offered by reducing the definition in the horizontal direction, with the possibility of reducing the vertical resolution if necessary, allied to the simplicity and accumulated experience with the conventional system, make the latter a strong favourite.

7. CONCLUSIONS

The three systems examined are each capable of reproducing television pictures in a bandwidth smaller than is required for the conventional system. The quality of reproduction was in each case noticeably inferior to that which can be achieved with the conventional system. When the reproduced pictures were compared with similar pictures produced in the same bandwidth by passing a conventional waveform through a low-pass filter and crispener circuit, none of the systems showed any marked superiority.

In view of this fact, and the considerable difference between the complexities of the instrumentations, it would appear that even for pictures having sufficient interest value to permit a reduction of picture quality, the conventional system operating with a reduced definition is likely to prove the most satisfactory.

One result of this investigation is that the authors have come to believe that where television is intended for broadcast entertainment, bandwidth-compression methods of the types investigated are unlikely to prove worthwhile. A useful reduction could not be achieved by such techniques without imposing new restrictions on the amount of fine structure in the picture. This fine structure is important in the reproduction of surface texture which can extend over relatively large areas and contributes greatly to the realism. It may be significant that almost all television development has been towards the attainment of a higher degree of realism in the reproduced picture.

8. ACKNOWLEDGEMENTS

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